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Smarter in Middle age, Faster in Old Age: A Cross-lagged Panel Analysis of Reaction Time and Cognitive Ability Over 13 Years in the West of Scotland Twenty-07 Study

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Abstract

Participants in the West of Scotland Twenty-07 study took reaction time tasks and the Alice Heim 4 Part 1 test (AH4) of intelligence twice, 13 years apart. Cross-lagged associations between speed of processing and AH4 were examined using latent variables in structural equation modelling. The stability coefficient of the latent trait of processing speed across 13 years was .49, and of AH4 was .89. There was a significant association (-.21) between AH4 at age 56 and speed of processing at age 69, but not vice versa. The results fail to support the theory that processing speed is a foundation for successful cognitive ageing, but support a hypothesis which suggests that higher general intelligence might be associated with lifestyle and other factors that preserve processing speed.

Keywords: aging, intelligence, reaction time, processing speed, longitudinal study, structural equation modelling

Smarter in Middle age, Faster in Old Age: A Cross-lagged Panel Analysis of Reaction Time and Cognitive Ability Over 13 Years in the Scottish Twenty-07 Study

As the proportion of older people in modern societies increases, there has been a greater emphasis on understanding the changes associated with ageing, especially cognitive ageing (House of Lords, 2005; Stern & Carstensen, 2000). Cognitive decline is often rated as the most feared aspect of ageing, and cognitive ageing is one of the costliest medical burdens for society (Martin, 2004; Stern & Carstensen, 2000). Cognitive deterioration is associated with loss of independence, lower quality of life, and an increased risk of mortality. Like other aspects of physical bodily functions, some mental functions decline on average as people grow older. Age-related declines in reasoning, memory, processing speed and other mental functions have been demonstrated in cross-sectional and longitudinal studies (Hedden & Gabrieli, 2004; Salthouse & Ferrer-Caja, 2003; Schaie, 2005). There are marked individual differences in cognitive ageing, with some people declining more over time than others (Schaie, 2005; Wilson et al., 2002). Finding the sources of these individual differences is a research priority.

Mental speed, or speed of information processing, has a long history as a potential explanatory construct in intelligence differences, cognitive development and ageing (Birren, 1964; Salthouse, 1996). It is generally assessed by tasks that involve items with simple mental content which would rarely or never result in incorrect solutions if there were no time pressure (Deary 2000; Salthouse, 1996). Thus, for example, psychometric tests like the Wechsler Adult Intelligence Scale’s digit symbol subtest or similar coding tasks are often employed to assess speed of information processing (Finkel, Reynolds, McArdle, & Pedersen, 2007; Hoyer, Stawski, Wasylyshyn, & Verhaeghen, 2004; Lemke & Zimprich, 2005; Salthouse, 2004;

Zimprich & Martin, 2002; Zimprich, Hofer, & Aarsten, 2004). On the other hand, arguably lower-level and more fundamental tasks such as reaction times, and even psychophysical backward-masking tasks such as inspection time, have also been used as processing speed measures (Deary, 2000; Salthouse, 1996; Hertzog, Dixon, Hultsch, & MacDonald, 2003). All of these processing speed measures are associated with psychometric intelligence differences in normal adults (Deary, 2000; Deary, Der, & Ford, 2001; Grudnik & Kranzler, 2001; Hoyer, Stawski, Wasylyshyn, & Verhaegen, 2004). Performance on all of them improves with development from childhood to adulthood, and declines with age (Der & Deary, 2006; Edmonds et al., 2008; Hoyer et al., 2004; Kail, 1991; Nettelbeck & Rabbitt, 1992; Salthouse, 2004).

The place of processing speed within an explanatory account of cognitive differences and cognitive ageing is ambiguous and disputed. On the one hand, speed of information processing may be viewed as just one aspect of cognitive functioning that deteriorates along with a number of others, with which it is correlated, and with which it might share aetiology (Finkel, Reynolds, McArdle, & Pedersen, 2005; Salthouse, 2004; Wilson et al., 2002). On the other hand, processing speed is sometimes viewed as a more fundamental construct, one which might explain some of the variance and age changes in other mental abilities, which it does more or less successfully (Finkel et al., 2007; Salthouse, 1996, 2001; Salthouse & Ferrer-Caja, 2003; Zimprich, 2002; Zimprich & Martin, 2002). In this latter view, speed of information processing is a “fundamental property of the nervous system” (Madden, 2001, p. 288), that subserves a diverse range of other mental functions; when processing speed is slower, the other mental functions are less well implemented.

Some of the evidence that underpins a processing speed account of cognitive ability and ageing is cross-sectional. There are moderately strong correlations between psychometric intelligence and non-psychometric processing speed measures such as reaction times and inspection times in normal adults (Deary, Der, & Ford, 2001; Grudnik & Kranzler, 2001), in children (Edmonds et al., in press; Fry & Hale, 1996), and older people (Nettelbeck & Rabbitt, 1992). Adjusting for individual differences in measures of processing speed such as digit symbol and reaction time often eliminates a majority of the age-related variation in more complex mental abilities (Salthouse, 1996; Zimprich, 2002). A meta-analysis showed that processing speed acted as a strong partial mediator of the effects of age on fluid intelligence and episodic memory (Verhaegen & Salthouse, 1997). On the other hand, Salthouse (2001), for example, did not find that a model which used perceptual speed as a mediating latent variable for the influence of age on other cognitive latent variables (reasoning, spatial visualization, recall memory, and paired associate memory) had better fit to the data than models which viewed age as having an effect on general cognitive ability, or reasoning as the mediating variable. The issue of whether processing speed is a correlate or cause of mental abilities cannot be settled with cross-sectional data.

Only limited longitudinal data exist on the processing speed hypothesis of cognitive ageing, as emphasised by Lemke and Zimprich (2005). There is evidence that the mediating effect of processing speed on the effect of age on other cognitive abilities is much less substantial using longitudinal designs (Sliwinski & Hofer, 1999; Zimprich, 2002). For example, Zimprich (2002) found that digit symbol test scores accounted for about 85% of the age-related effects on other Wechsler Adult Intelligence Scale subtests in a cross-sectional analysis, but only 4% in a longitudinal analysis with the same participants. Some have found larger mediating effects, but they are still far short of cross-sectional effects. For example, over a 4-year period in older people, changes in speed of processing correlated .61 (37% shared variance) with changes in memory (Lemke & Zimprich, 2005), and .53 (28% shared variance) with changes in fluid intelligence (Zimprich & Martin, 2002). Hertzog, Dixon, Hultsch, & MacDonald (2003) modelled cognitive changes across six years in the Victoria Longitudinal Study. They found some evidence for age-related changes in working memory and episodic memory being partly mediated via perceptual speed. On the other hand, they also report good fit to a model that construed perceptual speed and reaction time changes as a part of the general cognitive change that takes place with age. This ambiguity is similar to that reported by Salthouse (2001) with cross-sectional data.

Analyses of the Swedish Adoption/Twin Study of Aging have been especially informative. Longitudinal data with up to four testing occasions in old age found that for processing speed—measured using the psychometric tests of symbol digit and figure identification—the intercept was associated with reduced acceleration in the decline of memory and spatial ability, and that the slope of processing speed change was moderately associated with the slopes of verbal ability, spatial ability and memory (Finkel et al., 2005). Subsequent analyses, using bivariate dual change score models, and with up to five measurements occasions and 16 years of follow up, found some evidence that processing speed had a dynamic influence on later memory and spatial ability (Finkel et al., 2007). The same was not true between processing speed and verbal ability. Indeed, the dynamic association between verbal ability and later processing speed was significant, but not vice versa; these two cross-lagged associations were not significantly different. These analyses were performed using psychometric tests of processing speed.

There is still an open question concerning whether processing speed changes with age may be considered as a partial explanatory foundation for more general cognitive ability changes. Longitudinal data are especially valuable, but are rare, and rarer still with regard to large, population-representative samples tested across a long period of time. Moreover, it is important, if possible, to have measures of processing speed that are not complex psychometric tests, such as digit symbol-like tasks. In the present study we examine a large, population-representative, narrow age sample of people tested on simple and choice reaction times and a psychometric test of general intelligence, first at age 56 years and then again at age 69. We examine the associations between these variables for lead-lag effects that might contribute to the understanding of the importance of speed of information processing in the ageing of cognitive abilities from middle to old age.

Method

Participants

Participants in the present study are drawn from the West of Scotland Twenty-07 study—a population-based, longitudinal, multiple cohort study aimed at investigating the processes which create and maintain socially structured health inequalities. The design and sampling of the Twenty-07 study were described by Ford, Ecob, Hunt, Macintyre, and West (1994) and Macintyre et al. (1989). Briefly, the study comprises three age cohorts aged around 15, 35 and 55 years in 1987, each to be followed up for 20 years. They were selected as a two-stage random sample of the population of the Central Clydeside Connurbation, a large urban area in the west of Scotland centred on Glasgow City. The data used here pertain to the oldest cohort from waves 1 and 4 of the Twenty-07 study, which began, respectively, in 1988 and

2000, these being the only occasions when the Alice Heim and reaction time tests were both administered. No equivalent data are available for the two younger cohorts.

There were 679 people in total (303 men, 376 women) who met our selection criteria. Using the UK's standard six-category grouping of occupations, the sample was divided, from most professional to most manual, as follows: class I = 47, class II = 156, class IIIN = 108, class IIIM = 227, class IV = 98, class V = 43. As described elsewhere, the sample is unusually valuable in being representative of the background population (Deary & Der, 2005a, Table 1). The mean age of the sample at wave 1 was 56.1 (N = 679, SD = 0.6, range = 54.2 to 58.3), and at wave 4 was 68.9 (N = 524, SD = 1.0, range = 66.6 to 72.9). Therefore, the chronological age range at both waves was very narrow. Data were collected by trained nurses, typically in the participants' homes.

Cognitive ability

General mental ability was tested using the Alice Heim 4 Part 1 Test (AH4) of General Intelligence. Administration and scoring were carried out using the instructions in the test manual (Heim, 1970). The test overall has 65 items, from which the participant completes as many as possible in ten minutes. A practice test was given before the test proper. There are verbal and numerical reasoning items in the test, and separate scores were obtained for each subset. Of the verbal items: 11 are verbal opposites, 10 are verbal synonyms, and 11 are verbal analogies. All verbal items take the form of a stem and then provide five possible answer options from which the participant chooses one. The numerical items comprise: 12 series completion items, 11 arithmetic items, and 10 numerical reasoning items. For all numerical items, the answer must be written down and no answer options are given. Therefore, although the opposites and synonyms assess vocabulary, the verbal analogies and the three numerical types of item assess more fluid skills, including reasoning and working memory.

Reaction times

Simple and four-choice reaction times were measured using a portable device that was designed for and used in the UK Health and Lifestyle Survey (Cox, Huppert, & Whichelow, 1993). This was described in detail and illustrated by us previously (Deary, Der, & Ford, 2001). The device is a shallow, rectangular box. On the top face of the box there is a high-contrast LCD screen. Below that, there are five response keys arranged in a shallow arc and numbered, from left to right, 1, 2, 0, 3, 4. The simple reaction time test precedes the four-choice reaction time test. There are 8 practice trials and 20 test trials. The participant rests the second finger of the preferred hand on the 0 key. After a zero occurs on the LCD screen the participant presses the key as quickly as possible. The mean and standard deviation of the 20 simple reaction time trials are calculated. The four-choice reaction time test has 8 practice trials and 40 test trials. The participant rests the second and third fingers of the left and right hands on, respectively, the keys marked 1, 2, 3, 4. After a number appears on the LCD screen the participant presses the appropriate key as quickly as possible. Each of the four numbers appears ten times, in a randomised order. Separate means and standard deviations are computed for correct and incorrect trials. Data for correct trials only were used in the present study. For both the simple and four-choice reaction time trials there was a variable interval of between 1 s and 3 s between the participant's response and onset of the next stimulus. As described previously, only those participants with fewer than ten incorrect responses in the four-choice reaction time test were used in the present analyses (Deary & Der, 2005a). For the purposes of the longitudinal models conducted here, only the means of the simple and choice reaction time tasks were used.

Statistical analyses

Distributions of and associations between the cognitive test and reaction time variables are described using means, standard deviations and Pearson correlation coefficients. The reaction time variables (simple and choice reaction time means) were positively skewed at both time points. This was rectified by transformation using the negative reciprocal, and scaled by factor of 10000 for computational stability. The cross-lagged panel data formed from the reaction time and cognitive data in waves 1 and 4 are analysed using structural equation modelling (SEM), performed using the statistical package R (Ihaka & Gentleman, 1996). The SEM model contains eight observed variables: two reaction time measures and two AH4 measures at waves 1 and 4. There are four latent factors, two of which are exogenous; i.e. the reaction time and AH4 latent traits at wave 1. The data covariance matrix was estimated using a maximum likelihood procedure to impute missing values (Little & Rubin, 1987), as implemented by R's function 'mlest' in package 'mvnmle' (Ihaka & Gentleman, 1996). The fit to these data was compared to fits using the same model where the covariance matrix was estimated using pairwise complete observations, and also using complete cases only. There was negligible difference between these fits. For example, the comparative fit index was 0.993 for the imputed data and 0.990 for the complete-cases data. Model parameters were estimated by maximum likelihood using R's function 'sem' in package 'sem'. The starting values were the defaults chosen by the program. Goodness-of-fit indices for the imputed data are described in the results section.

Results

Means and standard deviations are shown in Table 1 for all participants who provided some data on the variables to be used in the present analyses (N = 679), and for the subsample with complete data (N = 414). The means and standard deviations for all participants were estimated using maximum likelihood. There are only small differences between them. Participants were, on average, about 13 years older at wave 4 than they were at wave 1.

Based on pairwise deletion of cases, participants scored less well on all four variables at wave 4 compared with wave 1: AH4 verbal, $t(428) = 5.82$, $p < .001$; AH4 numerical, $t(428) = 8.22$, $p < .001$; simple reaction time mean, $t(489) = 2.03$, $p = .040$; and four-choice reaction time mean, $t(489) = 5.30$, $p < .001$. The stability coefficients (Pearson correlation coefficients between these variables across time using pairwise elimination of data) of the four variables were as follows (all $p < .001$): AH4 verbal, $r(427) = .72$; AH4 numerical, $r(427) = .78$; simple reaction time mean, $r(488) = .38$; and four-choice reaction time mean, $r(488) = .56$. The correlation matrices between all variables—for all cases (these correlations were estimated using maximum likelihood) and complete cases—are shown in Table 2.

Ignoring, for now, the path weights in the model, the form of the structural equation model for the data is shown in Figure 1. The measurement model for the reaction time latent trait at waves 1 and 4 included simple reaction time mean and four-choice reaction time mean. The measurement model for cognitive ability at waves 1 and 4 included the AH4 verbal and numerical subtests. Stability coefficients for the reaction time and cognitive ability latent traits were included. The reaction time and cognitive ability latent traits were allowed to correlate at wave 1, as were their disturbance terms at wave 4. Both cross-lagged path weights were estimated (the F1 to F4 path was eliminated in our preferred, final model; see below), and their values, significance levels and difference were of principal interest. Associations are clearly constrained by the temporal sequence of measurement, and the markers of the two types of latent trait (reaction time and cognitive ability) are clearly separated.

Prior to model fitting we investigated the factorial invariance of the latent traits across time by fitting a series of models with increasingly restrictive equality constraints on model parameters. Parameters are constrained to be equal for the same measure taken at the two time points. We fit a hierarchy of three constrained models (Table 3). In the first constrained model, the factor loadings of corresponding measures at time 1 and time 2 are constrained to be equal in order to establish metric invariance (Horn & McArdle, 1992). In the second model the residual variances of corresponding measures at time 1 and time 2 are constrained to be equal, to explore the possibility of a difference in the amount of unexplained variance between the two time points. In the third and final model the intercepts associated with corresponding measures at time 1 and time 2 are constrained to be equal (though they were not expected to be so), resulting in a model that assumes the means are the same across the time points. Constraints are applied progressively: at each step the model includes the constraints applied in previous steps. At each step we compared the model's goodness of fit with the fit of the unconstrained model. These comparisons are presented in Table 3. The goodness-of-fit does not significantly deteriorate with respect to the unconstrained model until the final equality constraint (equality of means across time) is applied. We conclude from this that the model's factorial configuration explains the measurement variance-covariance structure at time 1 and time 2, and is not of itself biased by failing to account for extraneous effects introduced between the time points. We would of course expect performance to decline (change in intercepts) somewhat between these time points, as indicated by the difference in the above-described means.

The final model is shown in Figure 1. The overall model Chi square statistic for all data is 38.4 (d.f. = 14, $p < .01$). We attribute the slightly inflated (significant) model chi square to lack of multivariate normality in the sample distribution, and this was confirmed by a Shapiro-Wilks test ($W = .97$, $p < .01$). All the other goodness-of-fit indices suggest a good fit. The RMSEA was 0.051. The SRMSR was 0.022. The comparative fit index = 0.993. The highest absolute standardized residual was 0.07. All of the path weights in the model in Figure 1 have *p* values < .01. The only changes made to the model were: the addition of a correlated error term between the simple reaction time mean at waves 1 and 4; and the dropping of the non-significant path from F1 to F4 (standardized estimate = 0.05, $p = .07$). Note that the relative sizes of the path weights F1 to F4 versus F2 to F3 do not reflect the relative sizes of the relevant correlations in Table 2. This is due to the different stability coefficients of the two latent traits. A very similar example of this phenomenon may be seen in Rogosa (1980, Figure 4, example (e), p. 252). The model which included the path from F1 to F4 had a Chi square statistic of 35.0 (d.f. = 13, $p < .01$). The difference between this and the chi square for the final model is not significant, and the more parsimonious one (Figure 1) is preferred. Differences in parameter estimates between the two models, other than F1-F4 were less than or equal to .02. A model which omitted the path from F3 to F4 had a Chi square statistic of 101.7 (d.f. = 1, $p < .01$). The difference between this and the chi square for the final model is significant, and the final model (Figure 1) is preferred.

In the model shown in Figure 1 all of the manifest variables have moderate or high loadings on the associated latent traits. The association between the latent reaction time trait and the cognitive ability trait at wave 1 is -.49; people with higher AH4 scores take less time to respond. Note that this association is in a sample with very small chronological age variation. The stability coefficient of the cognitive ability latent trait (.89) across 13 years is stronger than the reaction time latent trait (.49). A principal concern is the relative strength of the two cross-lagged associations. There was a significant association (-.21) between the cognitive ability trait at wave 1 and the reaction time trait at wave 4. The association between the reaction time latent trait at wave 1 and the cognitive ability trait at wave 4 was non-significant. However, this does not mean that the two path weights are significantly different. Therefore, we conducted a likelihood ratio test comparing two models. These were similar to that in Figure 1, but had both F1 to F4 and F2 to F3 paths included. One of these models had an equality constraint imposed between F1 to F4 and F2 to F3. The other did not. This is equivalent to a direct test of the difference between these paths, analogous to SPSS/AMOS's 'critical ratio for differences'. When all data were tested, the model without the equality constraint fitted significantly better, Chi square = 7.0, d.f. = 1, $p = .008$. When those with complete data were tested, the model without the equality constraint tended toward fitting significantly better, Chi square = 3.1, d.f. = 1, $p = .078$. Thus, reaction time performance at wave 4 is associated with better previous reaction time performance and cognitive ability, but cognitive ability at wave 4 is associated with only prior ability on the same trait.

Discussion

Reaction times and the cognitive ability test scores obtained here show substantial stability across a period of about 13 years. The two constructs have a contemporaneous correlation, with those who score better on the verbal and numerical reasoning items having faster reaction times. As Lemke and Zimprich (2005) explained, this correlation on its own is valuable because, given the very narrow age range of the sample, it gives a speed-intelligence association that is orthogonal to age. The one significant cross lagged association—which was also significantly different from the other one—across the 13 year gap was not in the expected direction. It was the prior cognitive ability test score that was associated with the later efficiency of processing, rather than vice versa. It had been hypothesised that, as processing efficiency deteriorates from age 56 onwards, which it does (Deary & Der, 2005a; Der & Deary, 2006), it would lead the decline in verbal and numerical reasoning. Here, though, it was the AH4 scores that provided the lead variable. Lemke and Zimprich (2005) called the processing speed theory into question because processing speed and memory changes shared only 37% of variance over a four year period. Here, it may be called into question because of the lead-lag association found in the much longer follow-up period used here.

There are at least two possible explanations for this finding. First, it might be that people with higher cognitive ability make better use of limited practice in getting to know how to perform at their optimal level, even in quite simple tasks like reaction time. Thus, this would agree with findings that IQ is associated with the early stages of skill development (Ackerman, 1988). It would also accord with the finding that the amount of learning with a processing speed task in a single session is predictive of relative improvement in the same task across a six year period (Zimprich, Hofer, & Aartsen, 2004). The participants had experience of the reaction time device for only three brief periods: at waves 1, 3 (the wave 3 reaction time data were not included here; participants did not take AH4 at this time; see Deary & Der, 2005a) and 4, each for about 10 to 15 minutes. Therefore, even when it was seen for the third time across a period of about 13 years, it represented a quite novel task, to which the more cognitively able individuals might have become better accustomed.

Second, another possibility is that the cognitive ability contribution from wave 1 to reaction time performance at wave 4 might be more substantive. It is known that the reaction times gathered from the device used here are associated with later mortality. Those with slower reaction times, and those whose reaction times deteriorate more across a fixed period are at higher risk of earlier death (Deary & Der, 2005b; Shipley, Der, Taylor, & Deary, 2006, 2007). The AH4 test is a higher-level, more complex examination of cognitive function, and lower scores in middle age are also associated with higher mortality risk (Deary & Der, 2005b). It is likely that the AH4 test score contains variance on mental capabilities other than those associated with reaction time performance. It contains many items that call upon fluid reasoning and working memory skills with numerical and verbal materials, in addition to knowledge of word meanings. In addition, these additional capabilities might be associated with knowledge and thinking styles that help to preserve speed of information processing with age. Therefore, it might be the case that the relatively broad range of mental skills tapped by the AH4 test capture variance associated with living styles that militate against the age-related decline speed of information processing.

In part, the present results might accord with the findings of Finkel et al. (2007), with the Swedish Adoption/Twin Study of Aging. They found a significant dynamic effect from verbal ability, which they deemed to represent crystallised ability, to later processing speed, but not vice versa. However, it should be emphasised that these effects were not significantly different. The verbal and numerical reasoning items in the AH4 will draw upon vocabulary and number skills, which are relatively resistant to ageing (Schaie, 2005), though the items do involve active reasoning. On the other hand, the tests used by Finkel et al. (2007) to assess verbal ability included tests of information, synonyms, and analogies, and at least the last of these might involve active verbal reasoning[1].

Strengths of the study include the large number of participants who are reasonably representative of the background population. They were examined on the same mental ability and reaction time tests 13 years apart, and there were enough manifest variables to allow latent variable modelling. The processing speed measures were experimental-psychology-type reaction time measures, rather than psychometric tests, which tend to be used in most studies (e.g. Finkel et al., 2007). The latter are less satisfactory, because they have less well-controlled stimulus-response characteristics (Deary, 2000). This echoes the comment by Hertzog et al. (2003) that psychometric speed tasks tend to be relatively complex and, as such, result in artificially high correlations between processing speed and general mental ability. The study design is rare in answering Zimprich's (2002) comment that the age range of cognitive ageing samples is usually much larger than the time period covered by the study: here, the age range was very small and the time period much larger. The study is limited by there being only two occasions on which the variables were both examined, and by there being no assessments of cognitive ability before age 56.

Caution is needed in the interpretation of cross-lagged panels of correlations, particularly where the lagged variables have different stabilities. Rogosa's (1980) classic paper demonstrated that causal priority can be spuriously attributed to the variable with the lower stability. By taking the differential stability into account this can be avoided. His example (e) in Figure 4 discusses a situation similar to our findings here.

Further waves of data would allow for growth parameters to be estimated, and the observation of differing dynamic effects (Ferrer-Caja & McArdle, 2003). Therefore, non-linear ageing effects could not be examined. As with any longitudinal study, there were missing data. However, the models were run including only those participants with complete data and the results were very similar (data not shown, but available from the authors). It should be noted that any comments and conclusions that are made concerning processing speed are only relevant to the reaction time tasks that were used here. It cannot be assumed that other reaction time tasks and, more generally, other processing speed tasks—for example, psychometric tasks like digit symbol and psychophysical tasks like inspection time—would give the same results. Moreover, the general mental test used here was short and limited to verbal and numerical reasoning.

More definite information about the place of processing speed and its place in cognitive ageing will be known when the biological foundations of both are better understood. Evidence from the Swedish Adoption/Twin Study of Aging showed that there were substantial shared genetic influences between the intercepts of processing speed and the intercepts of verbal, spatial and memory ability and, similarly, between the accelerated declines of these abilities with age (Finkel et al., 2005). Processing speed was assessed using psychometric tests rather than reaction time. One candidate for a biological foundation of processing speed differences is the relative integrity of the brain's white matter, and some have suggested that reaction time mediates the influence of white matter integrity on more general cognitive ability in old age (Deary et al., 2006). It has also been shown, using voxel-based morphometric magnetic resonance imaging, that the regions of white matter that, if preserved in old age, are correlated with successful digit symbol performance are almost identical (72% of the voxels in common) to those associated with general mental ability (Staff, Murray, Deary, & Whalley, 2006).

In conclusion, the present data do not support the hypothesis that efficiency of processing speed contributes to successful ageing in a more general cognitive ability test. Rather, the reverse was found, provoking the suggestion that more omnibus mental tests capture some variance that is related to later advantages in processing speed.

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Footnote

[1]As suggested by a referee, we re-ran the structural equation models with the AH4 Verbal and Numerical reasoning scores individually. These two halves of the Alice Heim 4 part 1 correlate very highly (Table 2), indicating that, despite different surface content, they assess very similar reasoning skills. The crossed-lagged results are less clear when the Verbal and Numerical scores are run separately in models with processing speed. The findings from these models are available from the authors. We suggest that longitudinal models of processing speed versus verbal and numerical ability—i.e. examining each, specifically—would require multiple assessments of these abilities that were specifically designed for the purpose. What the present study achieves, ability-wise, is a reliable general ability/reasoning latent trait.

Table 1

Descriptive Data of Participants With and Without Complete Data

	Participants with complete data (N = 414)				All data (imputed using maximum likelihood) (N = 679)	
	Mean	SD	Skew	Kurtosis	Mean	SD
Alice Heim 4 Verbal, wave 1	15.4	5.0	0.22	-0.37	14.5	5.2
Alice Heim 4 Numerical, wave 1	14.7	5.7	0.01	-0.43	13.6	6.0
Alice Heim 4 Verbal, wave 4	14.3	5.1	0.33	-0.02	14.1	5.3
Alice Heim 4 Numerical, wave 4	13.2	5.9	0.08	-0.64	12.9	6.1
Simple reaction time mean, wave 1	339.0	100.2	2.00	5.40	346.8	104.2
Choice reaction time mean, wave 1	704.0	87.2	0.53	0.85	718.0	96.5
Simple reaction time mean, wave 4	354.2	115.7	1.61	2.62	357.7	119.9

Choice reaction time mean, wave 4	726.4	104.3	1.08	2.54	733.7	110.8

Table 2

Correlations Among the Variables Used in the Structural Equation Modelling

	1	2	3	4	5	6	7	8	Mean	SD
1. Alice Heim 4 Verbal, wave 1	-	.841	.720	.709	-.188	-.367	-.252	-.333	14.50	5.21
2. Alice Heim 4 Numerical, wave 1	.850	-	.746	.792	-.232	-.394	-.289	-.380	13.55	5.96
3. Alice Heim 4 Verbal, wave 4	.744	.758	-	.847	-.192	-.379	-.375	-.492	13.53	5.34
4. Alice Heim 4 Numerical, wave 4	.736	.800	.854	-	-.212	-.388	-.349	-.467	12.20	6.13
5. Simple reaction time mean, wave 1	-.234	-.261	-.224	-.236	-	.444	.364	.265	-31.08	7.08
6. Choice reaction time mean, wave 1	-.431	-.453	-.426	-.433	.510	-	.264	.547	-14.21	1.82
7. Simple reaction time mean, wave 4	-.267	-.292	-.364	-.349	.412	.314	-	.568	-30.19	7.85
8. Choice reaction time mean, wave 4	-.375	-.409	-.511	-.489	.311	.583	.582	-	-13.81	1.96

Note. Coefficients above the diagonal are for the 414 participants with complete data (listwise deletion). For descriptives see Table 1. Coefficients below the diagonal are for all cases (N = 679), calculated from the maximum likelihood estimate of the variance-covariance matrix.

For raw descriptives see Table 1. The mean and SD given here are the maximum likelihood estimates from transformed data using all cases.

These are included to allow re-modelling of data using the covariance matrix. RT values are -1/RT x 10,000.

Table 3

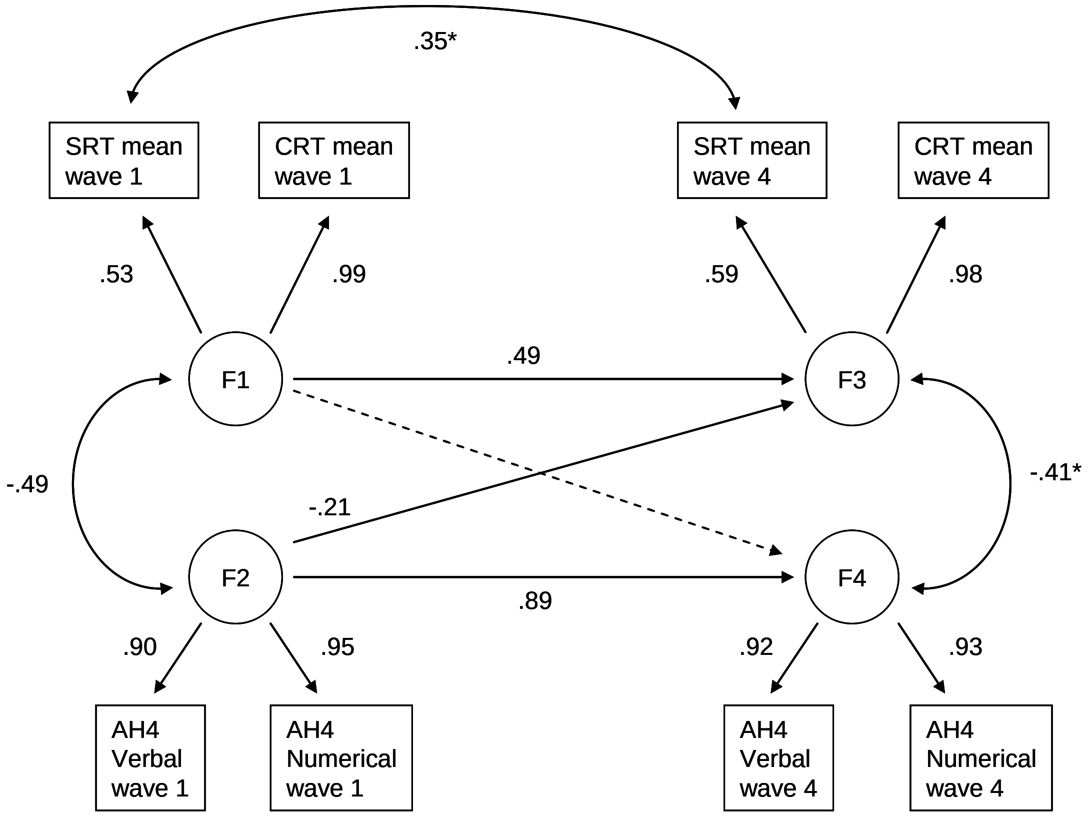
Results of Modelling Data for Factorial Invariance

Equality constraint	Model Chi square	Change in d.f.	Change in chi square	*p* for > in chi square
Unconstrained	31.08			
Factor loadings	33.73	2	2.65	.27
Residual variances	40.12	6	9.04	.17
Intercepts	111.51	10	80.43	<.001

Figure Caption

Figure 1. Results of the structural equation modelling of simple (SRT) and choice (CRT) reaction time and Alice Heim 4 Part 1 from age 56 to 69 in the Twenty-07 participants. This model is for all data, with missing values imputed by maximum likelihood (see text). Numbers alongside arrows can be squared to show the variance shared by adjacent variables. The dotted line represents the only pathway that was found to have $p > .05$ (this path was eliminated and the parameters re-estimated, and presented here). All others are $p < .01$. Path weights marked with an asterisk are covariances between residual (error or disturbance) terms. For fit statistics and model description see text.

Figure 1


.35*
SRT mean wave 1
CRT mean wave 1
SRT mean wave 4
CRT mean wave 4
.53
.99
.59
.98
F1
.49
F3
-.49
-.41*
-.21
F2
F4
.89
.90
.95
.92
.93
AH4 Verbal wave 1
AH4 Numerical wave 1
AH4 Verbal wave 4
AH4 Numerical wave 4